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COMPRESSION OF THE PLASMASPHERE DURING GEOMAGNETICALLY DISTURBED PERIODS

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ABSTRACT

Direct measurements of the thermal positive ions of hydrogen and helium have been obtained from positive ion mass spectrometers aboard the Orbiting Geophysical Observatories I and III. Observations made during 1965 and 1966 show distributions of H^+ and He^+ extending to altitudes as great as 40,000 kilometers, corresponding to a magnetospheric coordinate of L = 8. Typical H^+ profiles exhibit a comparatively gradual decrease in concentration with height within the plasmasphere. The outer boundary of the plasmasphere, however, is characterized by an abrupt decrease in the ion concentration. This boundary or plasmapause, defined by the reduction of H^+ concentration to 5×10^0 ions/cm^3 or less, is often quite sharp, with decreases in ion concentration of as much as an order of magnitude occurring within 250 kilometers or 0.1L. The position of the plasmapause is observed to move inward and outward from the earth in an inverse correlation with the planetary magnetic activity index K_p, indicating

significant large scale expansion and contraction of the plasmasphere during periods of agitated magnetospheric conditions. The magnetosphere was generally disturbed during the period 7-9 July 1966, with importance 2 solar flares occurring on the 7th, 8th, and 9th, and a sudden commencement of an extensive magnetic storm at 21:03 UT on 8 July. At 11:56 UT on 9 July, the H^+ boundary was observed to be unusually low, at 3.3L and at a local time of 00:45 hours. This observation is in sharp contrast with measurements of the plasmapause on both preceding and succeeding orbits, when in the absence of flares and magnetic disturbance the plasmasphere was observed to expand to L values as high as 6, at nearly the same local time. These results are consistent with measurements during a lesser storm which occurred on 25 June 1966, and with earlier observations of the disturbed plasmasphere obtained from the OGO I experiment. The apparent correlation between measurements of the hydrogen ion boundary and the "knee" whistler evidence of the plasmapause suggests that the mechanism responsible for the depletion of the ionization is effective along the lines of the magnetic field, extending well into the earth's inner atmosphere, to 1000 kilometers and below.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont.)

COMPRESSION OF THE PLASMASPHERE

DURING GEOMAGNETICALLY DISTURBED PERIODS

INTRODUCTION

Background

The behavior of the high altitude distributions of the positive ions of hydrogen and helium which with electrons make up the earth's thermal plasmasphere has been observed directly by rf ion spectrometers aboard the Orbiting Geophysical Observatory (OGO) I and III satellites. Measurements obtained during 1964-5 from OGO I [Taylor et al., 1965], [Brinton et al., 1966] and during 1966 from OGO III [Taylor et al., 1967] show that above 1,000 kilometers hydrogen and helium ion concentrations fall off rather slowly with altitude until the occurrence of the plasmapause, which is characterized by a sudden decrease in the ion number densities to 5×10^0 ions/cm^3 or less. The plasmapause, which was suggested by earlier direct measurements [Gringauz, 1963], has been studied extensively by whistler techniques [Carpenter, 1966] and has also been detected directly by the Faraday Cup experiment on the IMP-II satellite [Binsack, 1967].

A characteristic of the plasmapause which is of primary importance is the observed inward and outward displacement, which appears to be inversely related to magnetic disturbance. During very quiet magnetic conditions when $K_p < 1$ the plasmapause has been observed as far out as L = 8 [Taylor et al., 1967]. Conversely, subsequent to important disturbances, when $K_p > 5$ the plasmapause has been observed as close in as L = 2 [Carpenter, 1966], [Corcuff and Delaroche, 1964].

It is the purpose of this paper to present evidence of the behavior of the plasmasphere during the important solar flare events of 7 and 9 July 1966 and to compare these results to both earlier storm time data obtained from OGO's I and III and related whistler observations of the plasmapause.

The Experimental Equipment

The positive ion spectrometer experiments which were flown on the OGO I and III satellites are designed to measure ambient thermal ions in the mass range 1 to 45 AMU. The Bennett rf spectrometers used on the two flights are identical and provide a dynamic sensitivity range of approximately $5 \times 10^{\circ}$ to 1×10^6 ions/cm^3, with a resolution of 1 in 20 AMU. The spectral sweep rate, or time between consecutive samples of each ion detected is 64 seconds, which corresponds at plasmapause distances to a spatial resolution of approximately 250 kilometers and 0.1L. The instrumentation is described in detail in an earlier OGO data report [Taylor et al., 1965].

Location of Observations

Several important elements of the OGO III orbit are given in Figure 1. During June - July 1966 the orbit was inclined near 31 degrees, with a perigee

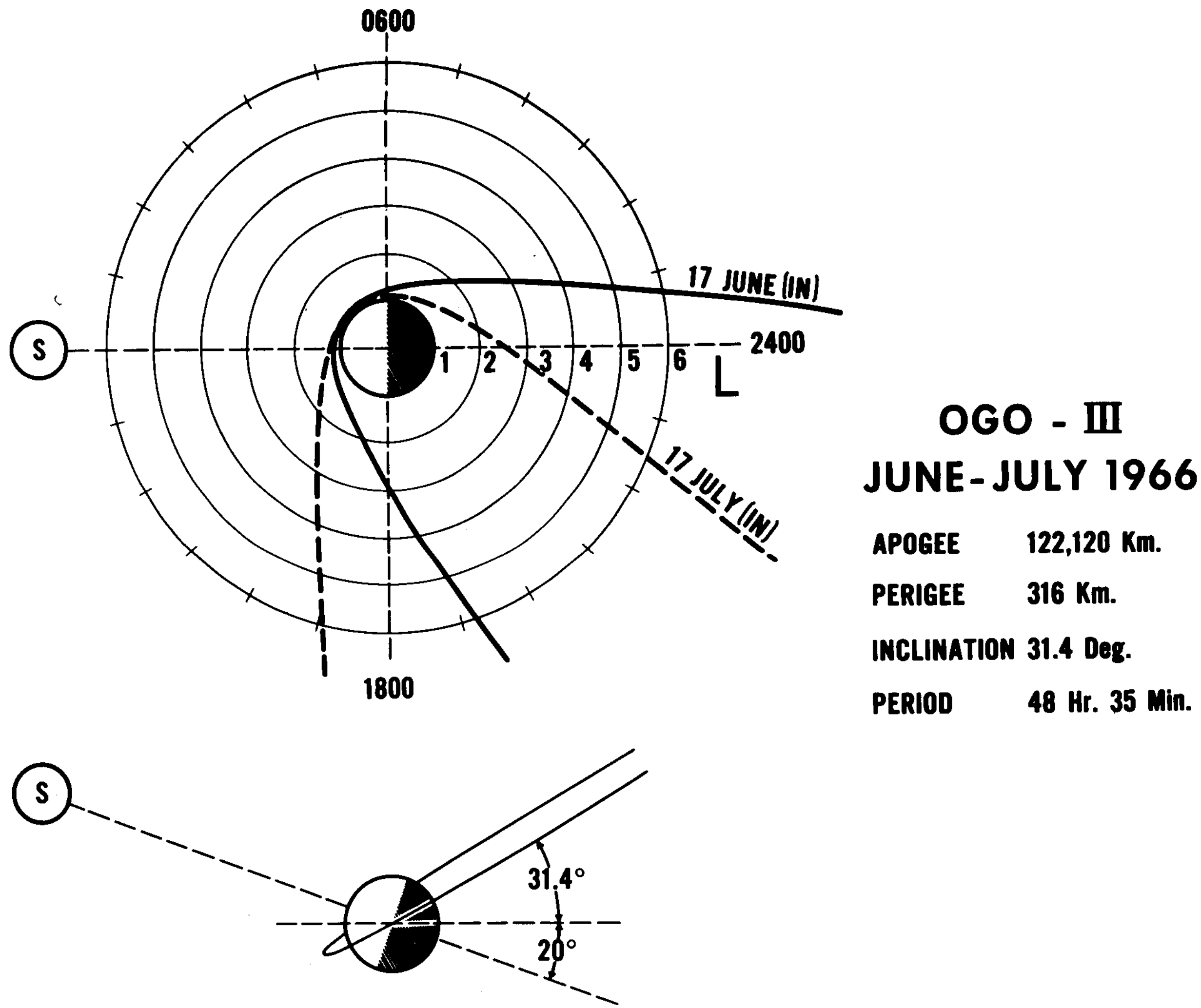

Figure 1. Characteristics of OGO III orbit during June-July 1966. Earth is viewed from above and displacement between geographic and geomagnetic equatorial planes is neglected. Solid and dashed curves are plots of satellite L and local time position for inbound and outbound arcs.

of about 316 kilometers and an apogee of about 122,120 kilometers. In July the inbound passes occurred near local midnight while the outbound passes were near dusk. In the region of interest, above $L = 3$, the rate of change of local time with respect to L is reasonably low, so that L or altitude is likely to be the primary variable observed in the data. The orbital period was nearly 48 hours, so that comparative spatial observations were possible at 2 day intervals.

RESULTS

Typical Undisturbed Profile

The OGO III data to be discussed first were obtained during the interval June to July 1966, when the operating attitude control system of OGO III permitted optimum data acquisition. Although the heavier mass ions of oxygen and nitrogen were observed at lower altitudes, this paper will treat only the high altitude H^+ and He^+ distributions which describe the plasmasphere - plasmapause region.

An example of high altitude light ion profiles is given in Figure 2. The concentrations of H^+ and He^+ observed on 19 July 1966 have been plotted against McIlwain's L parameter rather than altitude because these and other data so strongly suggest the geomagnetic control of the ion distributions. In Figure 2 each point represents a direct measurement of either H^+ or He^+. In the interval $L = 3$ to $L = 6$ the measurements are separated by approximately 250 kilometers.

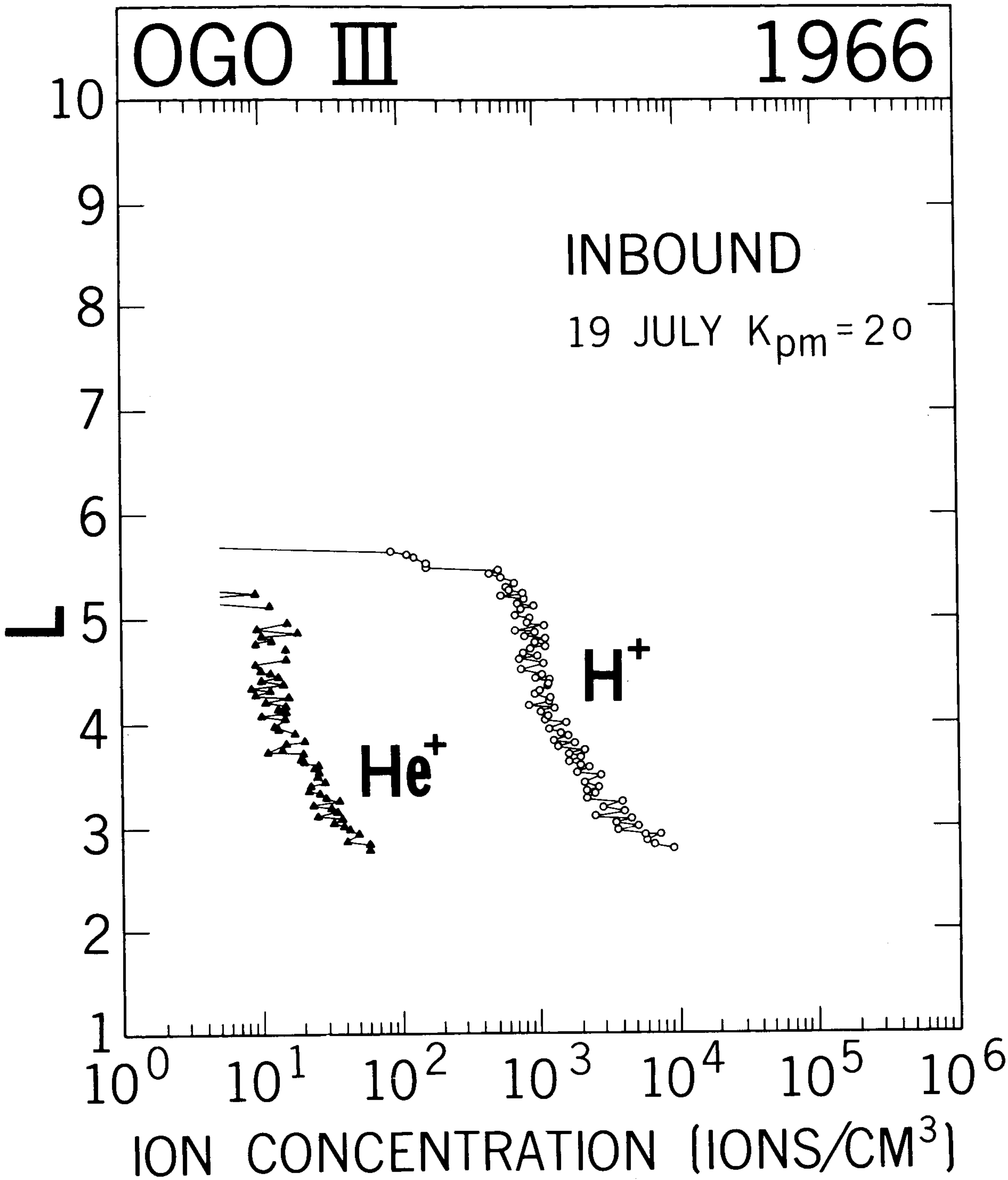

Figure 2. Profiles of hydrogen and helium ion concentrations plotted against McIlwain's L parameter showing typical example of plasmapause. The notation K_{pm} refers to the maximum value of the planetary magnetic activity index, K_p, recorded during the 24-hour interval prior to the time of plasmapause observation.

Occasionally the data points in a profile are not connected, which results from gaps due to telemetry noise, calibration, or other artificial effects. Due to interference affecting the most sensitive amplifier channel, the limiting sensitivity which can be realized with machine data processing is 5×10^0 ions/cm^3. Accordingly, the upper portions of the H^+ and He^+ profiles terminate at the 5×10^0 ions/cm^3 position. The lower portion of the profiles is terminated below about L = 2.7 because of gaps in the data processed to date.

The rather smooth decrease evident in the profiles of H^+ and He^+, followed by the sharp depletion of ions between L = 5 and L = 6 is fairly typical of other undisturbed passes of OGO III. These profiles are also representative of smoothed H^+ and He^+ profiles obtained during 1964 from OGO I [Taylor et al., 1965].

Determination of the Plasmapause

In Figure 2 the plasmapause is defined by the decrease in H^+ to 5×10^0 ions/cm^3 or less, which occurs at approximately L = 5.7. With the limiting sensitivity at 5×10^0 ions/cm^3, and assuming that at the boundary the H^+ concentration may drop below this level, it becomes necessary to establish some criterion for specifying the onset of the plasmapause. This is particularly true on passes in an expanded plasmasphere, when the plasmapause occurs at greater distances, after the ion concentrations have slowly decreased to levels close to

10^2 ions/cm^3 or less. Accordingly, we have limited our study of plasmapause events to profiles which exhibit sharp decreases of at least an order of magnitude occurring within a spatial range of 0.5L or less.

Displacement of Plasmapause vs. Magnetic Activity

In order to better establish a basis for the comparison of undisturbed data with the distributions obtained near the proton flare events of 7-9 July 1966 and the other storms to be considered, all of the OGO III passes available during June and July 1966 have been examined, applying the criterion described above. Although the effect will not be treated in this paper, it was observed that on profiles obtained on outbound passes in the dusk quadrant of the magnetosphere the plasmapause occurs at approciably higher L positions than on inbound passes. This suggests a distinct local time asymmetry in the plasmasphere which has been observed in the whistler data [Carpenter, 1966] and predicted in models of the plasmasphere proposed by Nishida [1966] and Brice [1967]. As a result of the observed asymmetry, we have chosen to examine the general correlation of plasmapause position with magnetic activity only in the data obtained in the midnight local time quadrant where local time variations are believed to be less pronounced.

The plasmapause positions observed on 18 inbound H^+ profiles are summarized in Figure 3. The dots represent observed steep gradients or plateaus,

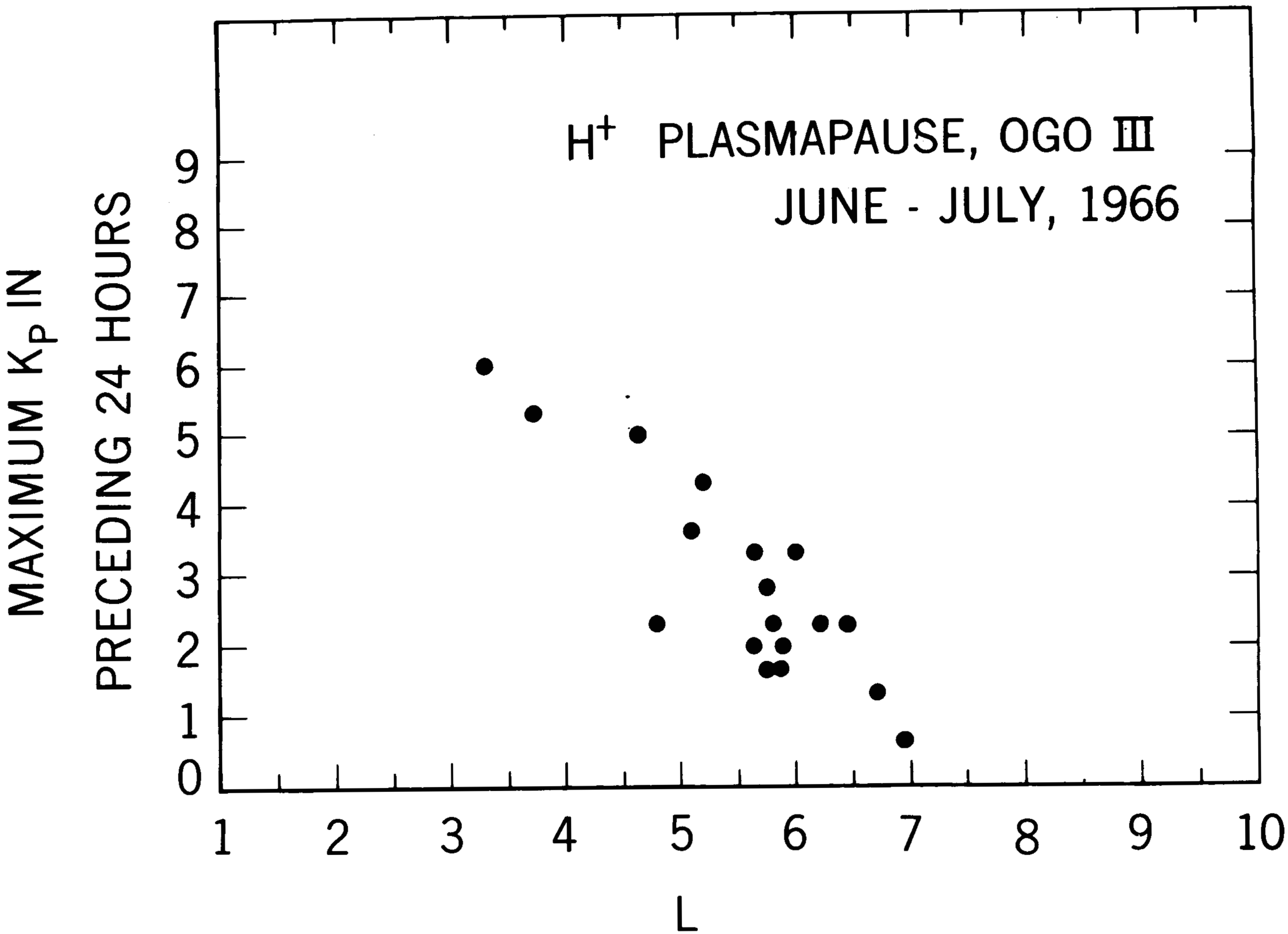

Figure 3. Positions in L of observed H^+ 'plateaus' or plasmapause events, plotted against the maximum K_p recorded during 24-hour period prior to each event. Selection of longer or shorter prior periods for K_p results in less correlation. To avoid possible uncertainties due to local time effects, only events observed on inbound passes near local midnight are considered.

which are clear examples of the plasmapause. The L coordinates of the plasmapause events are plotted against the maximum value of the planetary magnetic activity index K_p recorded in the 24 hour period prior to the plasmapause observation. These measurements occurred in a region between 22:45 hours and 01:15 hours local time and in a geomagnetic latitude interval of -16 to +14 degrees. The inverse relationship between L and K_p is evident, with the extremes in magnetic activity clearly correlating with the extreme positions of the plasmapause. In studying the profiles from which Figure 3 was derived, it is apparent that the K_p versus L relationship is not a simple, linear one, and that for moderate magnetic activity, when K_p is near 2, a fine correlation is difficult to obtain. The relationship observed between K_p and plasmapause L in these data is quite similar to that determined from whistler data for the period June - August 1963 [Carpenter, 1967a], as shown in Figure 4. It is evident that the slopes of the profiles suggested by the two sets of data are quite similar although the OGO III results indicate generally higher L values. It should be noted that the whistler results were obtained near local dawn while the OGO III results were obtained near local midnight, which may suggest a local time effect in the position and behavior of the boundary. In addition, the whistler data were obtained earlier in the solar cycle, which might account for the suggested 'expansion' observed in the OGO III data, taken during a generally more active solar period.

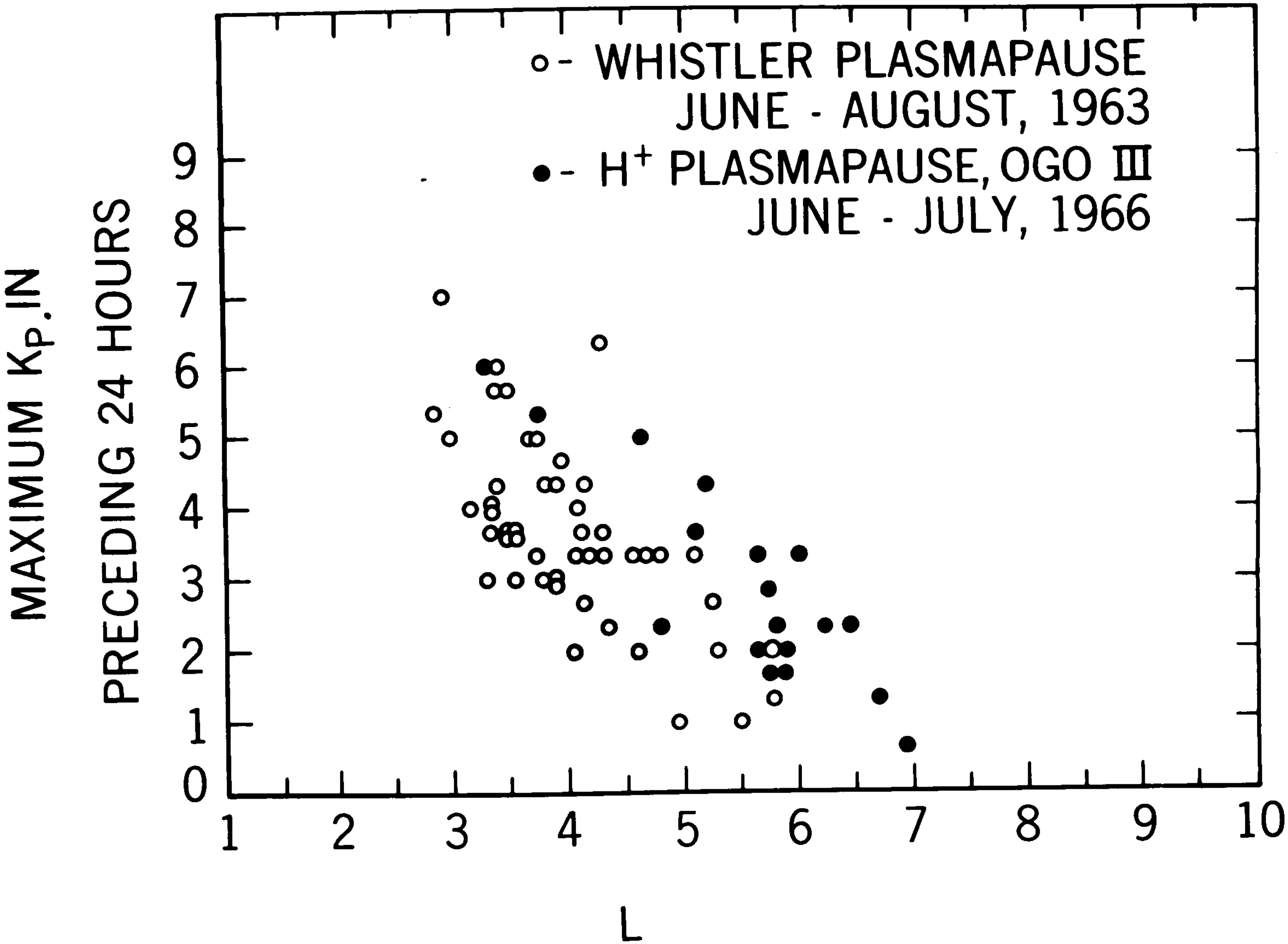

Figure 4. OGO III plasmapause events of Figure 3 plotted with earlier whistler observations of plasmapause, as a function of maximum K_p in prior 24-hour period. Whistler data, obtained near local dawn, are in terms of distance to plasmapause at geomagnetic equator, or L, while OGO III events were obtained at L positions which correspond to varying geomagnetic latitudes, between -16° and $+14^\circ$.

Effects of Solar Flare Events

The magnetosphere was generally disturbed during the period 7-9 July 1966, with importance 2 solar flares occurring on the 7th, 8th and 9th and a sudden commencement of an extensive magnetic storm, beginning at 21:03 UT on 8 July. During the week prior to this storm period, the magnetic activity was comparatively low. The nearest pre storm data now available is shown in Figure 5, which is a plot of H^+ concentration versus L obtained on 3 July 1966, when the maximum K_p in the previous 24 hours (defined as K_{p_m}) was $K_{p_m} = 2^+$. In this figure and in those to follow only the H^+ profiles are shown for simplicity. In all cases, the minor component He^+ profiles closely parallel the H^+ profiles as shown in Figure 2. The H^+ distribution of Figure 5 is, like that of Figure 2, fairly typical of the H^+ distributions seen during low activity and shows the plasmapause at $L = 6.4$ which corresponds to an altitude of 34,300 kilometers.

In contrast to the H^+ profile of Figure 5, which serves as a reference, the profiles of Figure 6 illustrate the strong inward displacement of the plasmapause during magnetic disturbance. As shown in Figure 6, on 9 July the plasmapause has moved inward to $L = 3.3$ at 13,400 kilometers altitude. This observation occurred at 11:56 UT, near the highest magnetic activity of the period which was $K_p = 6o$, which occurred earlier in the day, centered about 0600 hours UT.

On 11 July the plasmapause recovered partially, occurring at $L = 4.7$ and 22,400 kilometers. This observation occurred at 11:55 UT, approximately

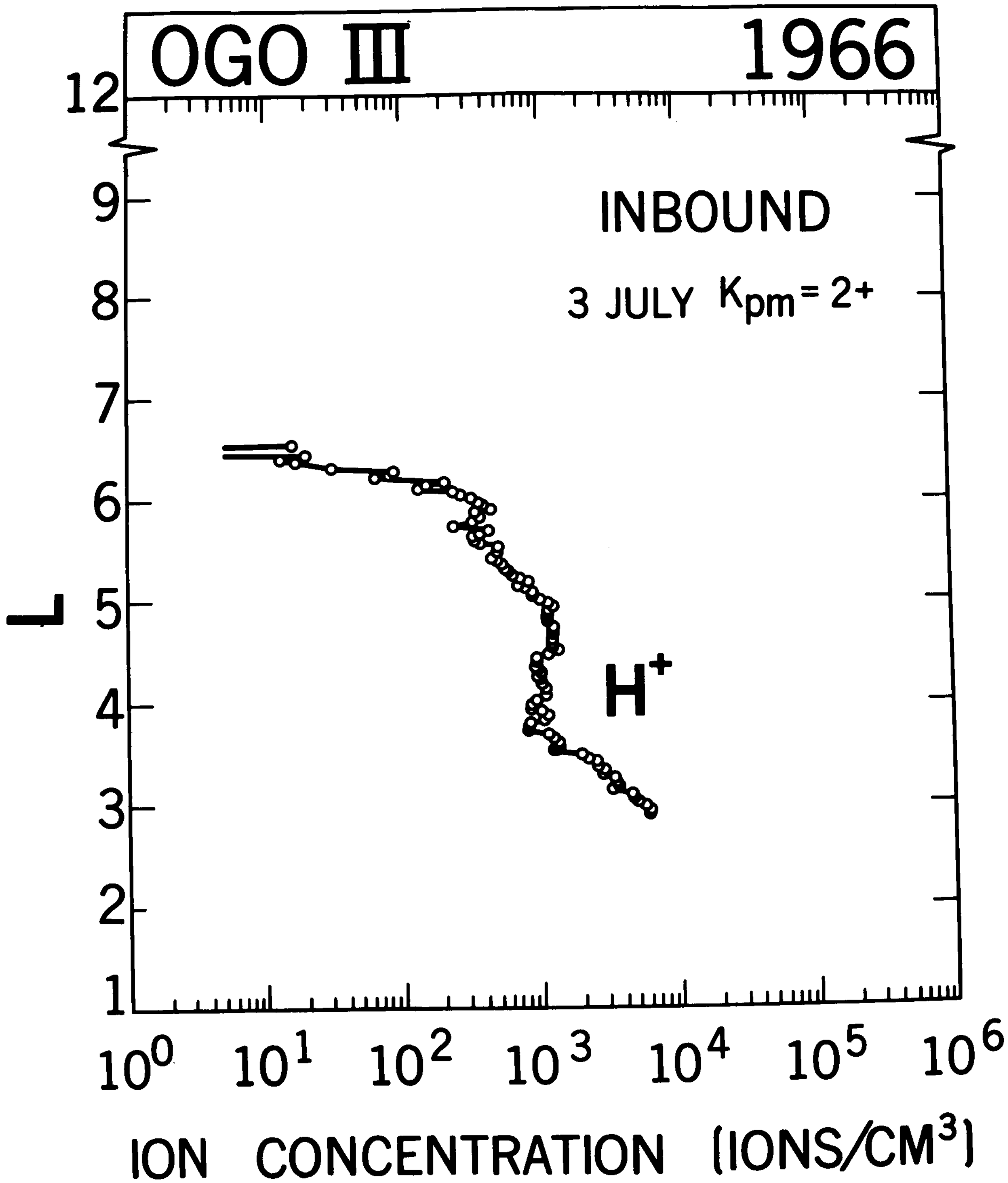

Figure 5. Pre-storm hydrogen ion profile showing plasmapause at L = 6.5 for K_{pm} = 2+.

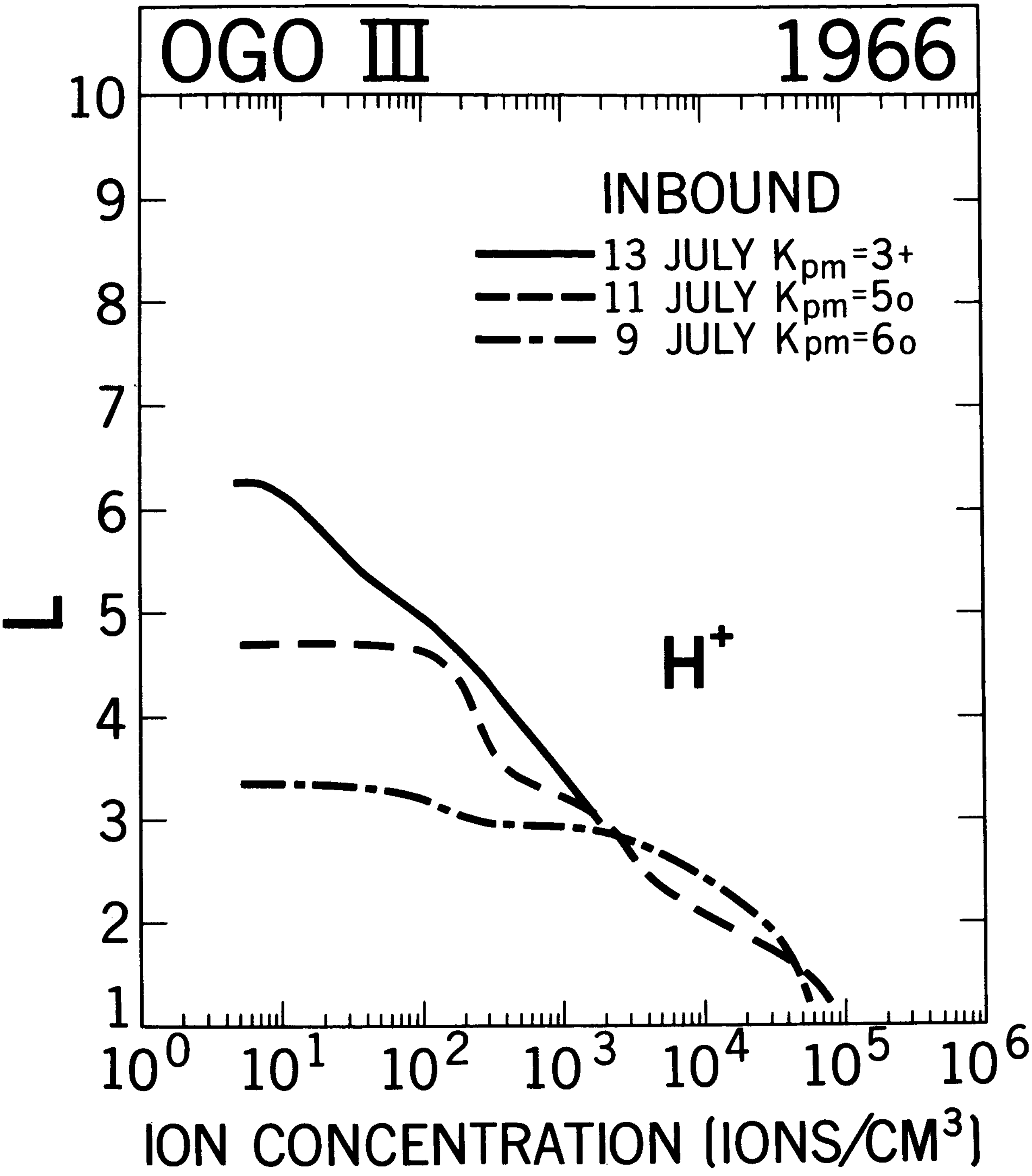

Figure 6. Smoothed hydrogen ion profiles from OGO III showing plasmapause inward displacement and subsequent recovery in L during proton flare period of 9 July. Data sampling rate required smoothing of raw profiles which are otherwise identical to those shown previously.

24 hours after the secondary maximum in the storm, when $K_p = 5$, centered about 0900 hours on 10 July. Finally, on 13 July at 11:39 UT, the plasmapause recovered to approximately 6.3 L, at 33,000 kilometers. The highest magnetic activity in the prior 24 hours occurred in the 0900 - 1200 hour interval on 12 July, when $K_{pm} = 3+$. It may be noted that although the H^+ profile of 13 July indicates a significant recovery from the intense portion of the storm, a comparison with the H^+ profiles of 3 July and 19 July suggests that the recovery is not yet complete.

Earlier Storm Data

An inward displacement of the plasmapause comparable to that seen on 9 July 1966 was observed during a less intense storm which occurred on 25 June 1966. In Figure 7, H^+ profiles obtained from OGO III on 23, 25, and 27 June show a pronounced relationship to the magnetic disturbance which reached its peak at $K_p = 5+$ in the interval 1800 - 2100 on 24 June. On 25 June, approximately 12 hours after the peak of the storm, the plasmapause was seen at L = 3.75. Prior to the passes on 23 and 27 June, the magnetic activity was significantly lower, and the plasmapause was observed to have moved outward to positions near L = 6, typical of low magnetic activity.

The indicated displacement of the plasmapause seen in the OGO III results is consistent with similar observations from nearly identical measurements

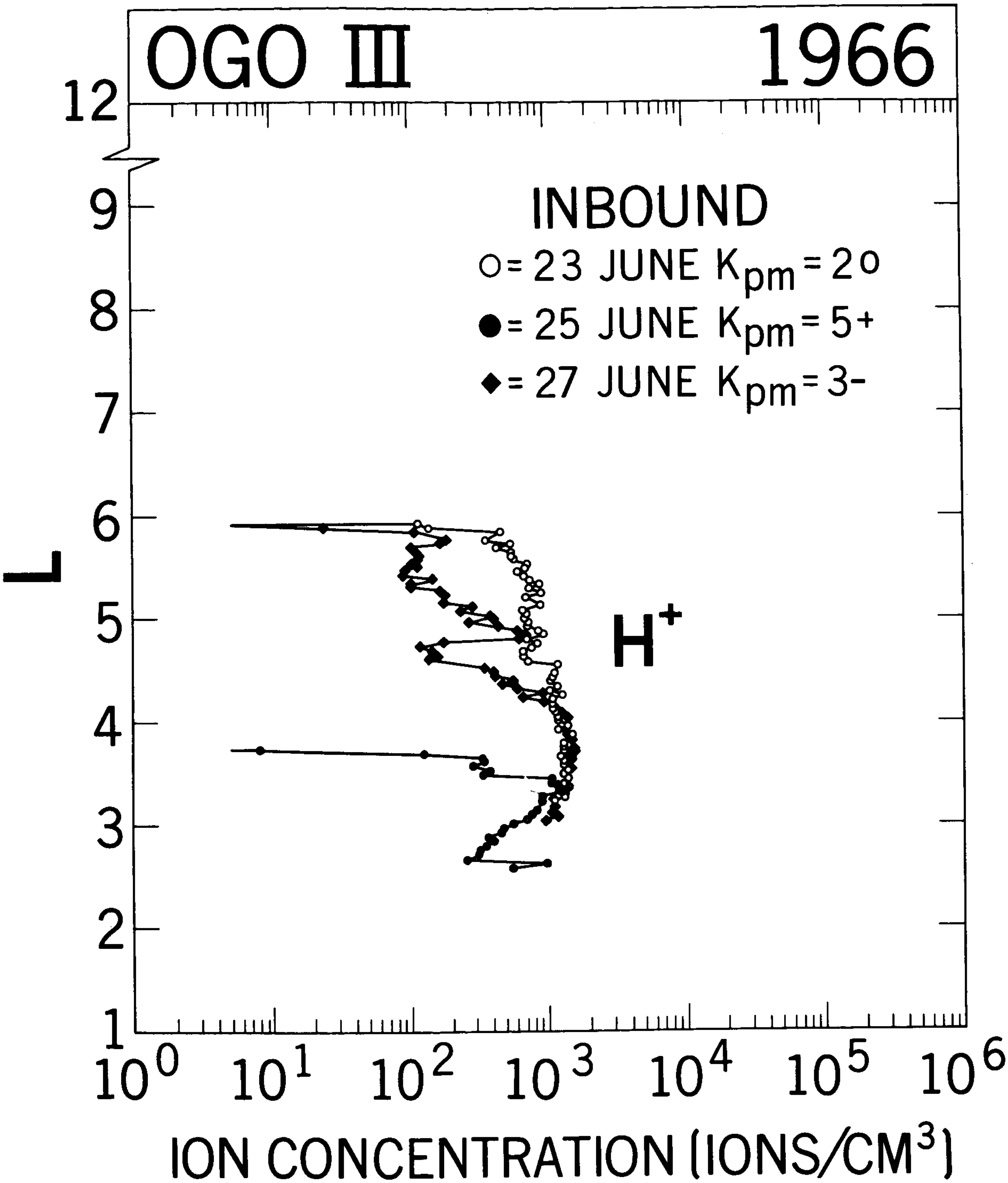

Figure 7. Profiles of H^+ concentration from OGO III, showing inward displacement of plasmapause following magnetic storm which reached K_p = 5+ on 24 June. Profiles are terminated prior to perigee due to gaps in accessible data. Fine structure, evident in the 25 and 27 June profiles will be the subject of a separate paper.

obtained in 1965 from OGO I. Results from a series of 3 inbound passes obtained during early morning are given in Figure 8. At 10:26 UT on 17 June 1965, the plasmapause was observed at L = 3.4, and 6,200 kilometers. This event was preceded by the height of the magnetic storm, when K_p = 7- between 1800 and 2100 UT on 16 June. A solar flare of importance 2 occurred near 0800 UT on 15 June. On an earlier pass of 9 June the magnetosphere was also disturbed, though less severely, and at 10:13 UT the plasmapause occurred at L = 4 and 8,500 kilometers. The maximum activity in the prior 24 hours occurred between 2100 and 2400 UT on 8 June, when K_{p_m} = 4-. While the pass obtained on 1 June, during low magnetic activity, is incomplete, it nevertheless suggests the undisturbed H^+ profile which was characteristic of the prior low magnetic activity period, when the plasmapause occurred above at least L = 5 or 22,500 kilometers. Unfortunately no data are available just after 17 June, which prohibits the documentation of a subsequent plasmapause recovery.

DISCUSSION

The Plasmasphere and Magnetic Activity

It is evident from the data obtained from OGO I and III that the envelope of light ions surrounding the earth and extending to great altitudes expands and contracts in a manner that correlates well with important changes in geomagnetic activity. This phenomenon has been observed repeatedly in whistler data

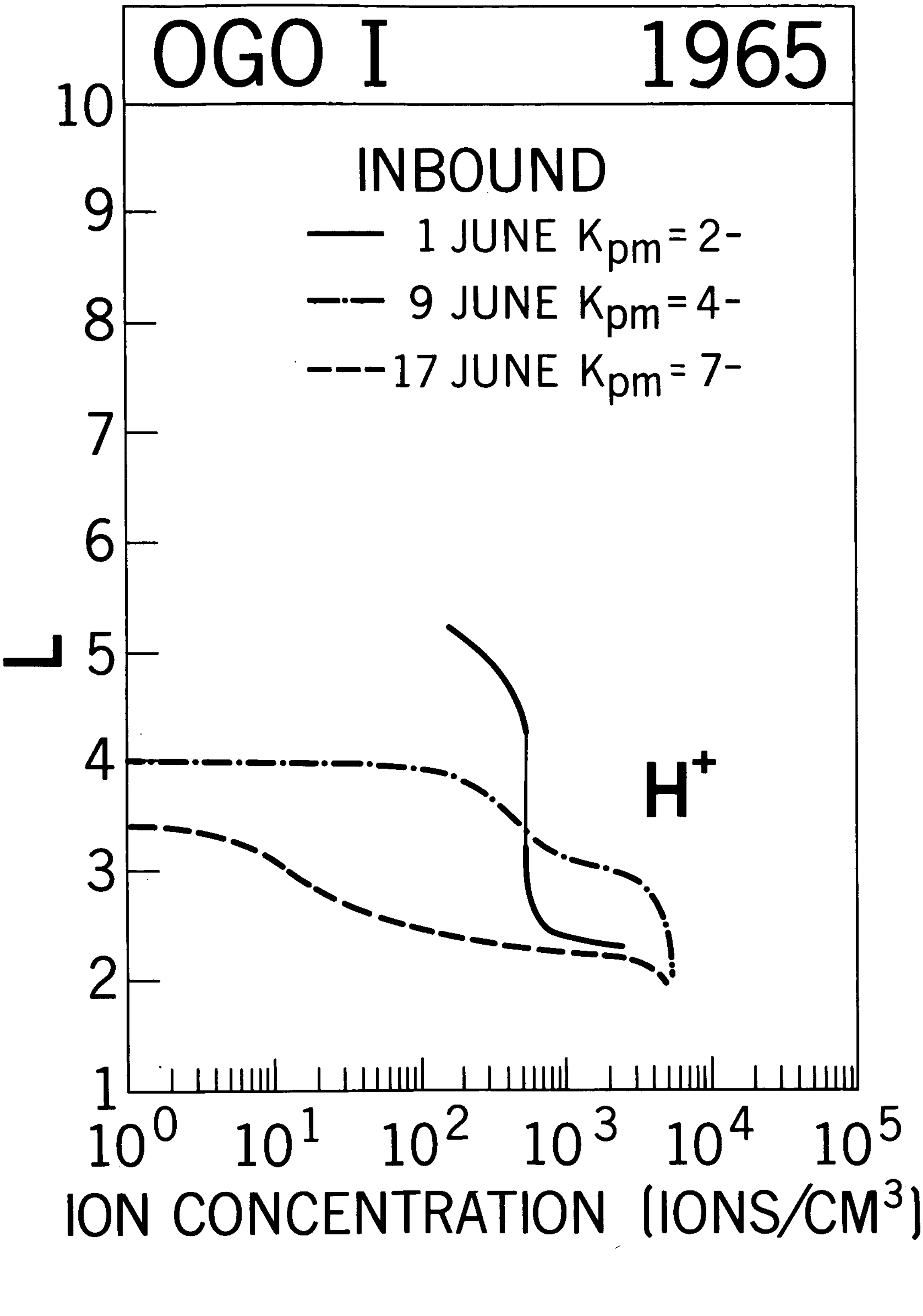

Figure 8. Smoothed hydrogen ion profiles from OGO I showing compression of plasmaphase during high magnetic activity on 17 June and subsequent recovery. Solid curve for pass of 1 June is incomplete above L = 5 due to gap in data coverage, and is interpolated between L = 3.2 and L = 4.2 (light line) due to additional gap in data coverage.

[Carpenter, 1967a] and in plasmapause observations made with the MIT Faraday Cup experiment [Binsack, 1967]. It is quite significant that the L coordinate of several of the plasmapause events detected by OGO III and OGO I agree with simultaneous ground based and satellite VLF observations [Carpenter, 1967b]. This evidence seems particularly important in the light of the study made by Carpenter and Stone [1967] of the behavior of the plasmasphere during a polar substorm. The whistler data showed that on the night side of the earth, rapid inward motions of the plasmapause occurred, of the order of 0.4 earth radii/hour, which were closely associated with depressed magnetic field levels recorded at the earth's surface during polar substorms. The electric and magnetic field distortions which may be associated with the rapid displacement of the plasmapause are considerable, and suggest that very large scale thermal plasma motions occur subsequent to solar disturbances.

Other evidence relating to plasma motions is found in the observations by Cahill and Bailey [1967] of field distortions which are attributed to inflation of the magnetosphere by low energy particle ring currents detected by Frank [1966]. It is significant that a similar inflation of the magnetosphere was detected by Cahill [1967] on June 17, 1965, during the same period when the plasmasphere was observed by OGO I to be greatly compressed. This appears to relate directly to the observations by Frank [1967] of low energy protons and electrons during July 1966 from OGO III. On 9 July 1966 Frank observed a strong enhancement of protons in the $31 \leq E \leq 49$ KeV range which appears to coincide with the location of the H^+ plasmapause observed from the same satellite. Important though lesser enhancements reported by Frank in the OGO III proton distributions on 11 and 13 July 1966 also appear to coincide in L position with our observations of the plasmapause. Assuming that the bunching of these particles into ring currents results in magnetic field depressions and attendant plasmasphere compressions such as those observed by Carpenter and Stone [1967], these independent energetic and thermal particle observations may prove to be quite consistent.

Magnetosphere-Ionosphere Coupling

The high altitude decrease in ion concentration is believed to be directly associated with the high latitude trough or depletion in H^+ and He^+, observed in a polar orbit near 1000 kilometers on OGO II [Taylor et al., 1966]. Although no simultaneous OGO II data is available for comparison with the OGO III storm data, comparison of earlier OGO II trough data with OGO I plasmapause events strongly suggests that the two phenomena may have a common origin. It is believed that the magnetospheric ion population results from the upward diffusion of H^+ and He^+ along magnetic field lines from the lower ionosphere. Accordingly, strong latitudinal gradients in the light ion concentrations in the source region would result in high altitude ion concentration gradients, across associated field lines.

The foregoing assumptions would be consistent with a magnetospheric model in which field lines above the plasmapause and trough are open, while field lines within the plasmasphere are closed. In such a model, similar to those proposed by Dessler and Juday [1965] and later by Nishida [1966] and Brice [1967], the high latitude depletion of ionization could be explained by the escape of H^+ and He^+ along the open field lines. However, during magnetic storms such as that of 8-9 July 1966, the plasmapause has been observed as near to the earth as $L = 3.3$, which in a simple dipole field model corresponds to a geomagnetic latitude of 56 degrees. While existing magnetic field models do predict open field lines, this phenomenon is proposed to occur well above $L = 3.3$. The question of whether magnetic field lines can be distorted or opened to such low latitudes is an open question. However, the observed buildup of energetic protons and electrons at the same L coordinate as the plasmapause is believed consistent with that possibility.

The mechanism responsible for the observed compression of the plasmasphere is not fully understood. Whether the observed behavior results from a large scale, field induced plasma motion, or emanates from rapid thermal and chemical changes produced by particle precipitation into the high latitude lower ionosphere remains to be determined. This question will be the subject of further studies of the data obtained from the OGO satellite series.

CONCLUSION

Positive ion spectrometer results from OGO III during June-July 1966 provide profiles of H^+ and He^+ to altitudes as great as 40,000 kilometers in the magnetosphere, where L = 8. Within the plasmasphere the H^+ profiles fall off rather smoothly with altitude and L, from concentrations of the order of 10^4 ions/cm^3 near L = 2. At the plasmapause or outer edge of the plasmasphere, the H^+ concentrations decrease very rapidly to concentrations of 5×10^0 ions/cm^3 or less. The He^+ profiles closely parallel the H^+ profiles, at a concentration typically lower by a factor of nearly 100.

The location of the plasmapause crossings observed near midnight local time is found to vary noticeably with magnetic activity, with an inverse correlation between the L coordinate of the plasmapause and the maximum value of K_p in the 24 hours preceding the event. These results, compared with whistler measurements of the plasmapause indicate large scale expansion and contraction of the plasmasphere relative to specific magnetic storms.

Associated with solar flare events occurring on 7-9 July 1966 and 15 June 1965, the plasmasphere is observed to be displaced inward to L positions as low as L = 3.3, following $K_p \geq 5$, in contrast to quiet magnetic conditions when the plasmasphere expands to L = 6 or higher.

Apparent correlations between enhancements of energetic protons and electrons, inflation of the magnetosphere, and large scale plasma motions, indicate that high altitude measurements of thermal particles may provide an important tool for the investigation of dynamic processes in the magnetosphere.

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